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Oil Palm Roots Architecture in Response to Soil Humidity

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ABSTRACT

Oil palm (*Elaeis guenesis*) is one of the most important estate crop commodities in Indonesia. The root is one of the plant organs which plays a vital role in plant growth and palm oil production. The objective of this research was to determine the architecture of oil palm roots in response to soil humidity in the root zone in its initial water footprint system. Destructive and non-destructive methods were used to determine the roots' parameters, i.e. root depth, root length and root density of oil palm age of mature plants. The result showed that depending on the type of the plant material and the soil, oil palm roots could grow horizontally reaching more than 6 m and vertically about 1.5–5 m. Dead primary roots were soon replaced by new ones. Primary roots predominantly served to structurally support the plant so that this root may grow into deeper layers of the soil. Secondary roots generally spread evenly and act as an anchor of the plant body to the ground which in turn strengthen the plant stand. Active horizontal root nets are always renewed with new roots arising from the stem-ends of the palm. The horizontal root nets were located on a radius of 0–1.5 m of a depth of 0–0.4 m, which were very solid for primary, secondary, tertiary and quaternary roots as well as the nets. This condition actively changed the dead roots with new roots. The root mat is very unique, forming a nest mat that can capture and control water availability in the environment of the soil surface around the growing space of oil palm. The architecture of oil palm roots has naturally adapted to form a root system that can conduct a mechanism to maintain soil water balance. The water footprint system was only active at the surface zone (0–0.8 m), while deeper than 0.8 m it was more affected by local aquifer condition.

Keywords: lateral roots, roots characteristic, soil water content, water footprint

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INTRODUCTION

Oil palm (*Elaeis guenesis*) is an important plant producing oil for food, oil for industry, and biofuel. Indonesia is currently the world's first palm oil producer. Oil palm is widely cultivated in Indonesia, consisting of 2 species, namely *E. guineensis* and *E. oliefera*. The former is the most cultivated type. Each species of oil palm has a distinct advantage. *E. guenesis* has a very high production potential, whereas *E. oliefera* has a low production potential. Generally used oil palm cultivars are divided into 4 different cultivars, namely macrokaria, dura, pisifera and tenera (Verheye 2010).

Oil palm can grow in all soil types; the average plant height reaches 20-30 m above soil surface. The canopy of the plant has an average width of 3-4 meters, and the oil palm can grow well at an alti-tude of 300-400 meters above sea level (Verheye 2010). Generally, the oil palm stem is soaked below the ground up to 90 cm, with the secondary roots of oil palm crops beginning to be found at a depth of 15-20 cm, and the tertiary roots are soaked to a depth of 90 cm and spread along 2 m from the pri-mary stem. The primary root is found at a depth of 90 cm, and in certain conditions can be found up to 2 m inside the ground (Jourdan & Rey 1997).

The root is one of the most important part besides the leaves and stems (Lynch 1995; Lynch 2011). It plays a vital role in plant growth and palm oil production. The root characteristics are part of the plant; it usually grows inside the ground, with the direction of growth to the center of the earth (geot-ropism), no tidal books (supporting leaves or scales), whitish or yellowish in color, and continuously growing at the tip side, but generally the growth is still lower than the stem, tapered end shape making it easier to penetrate the soil (Atkinson 2000). Oil palm belongs to the fibrous root plant with the following root structure: primary, secondary, tertiary, and quaternary fibrous roots, and root cap (calyptra), i.e. the lower-ends of the root, consisting of tissue used to protect the young and weak root tips (Fatmawati & Ginting 1987).

Palm roots can help in maintaining the growing environment balance system. This condition occurs as seen in the dry season grass under the palm trees that do not dry quickly, which means that the soil humidity in this environment is quite optimal. This is thought to be the result of changes in the porosity of the soil caused by the formation of oil palm root system. Normal growing palm roots will reach a depth of 2-5 m, depending on the severity of the soil texture (Tinker 1976; Hartley 1977; Fatmawati & Ginting 1987), and horizontally it can reach more than 4.5 m away from the stem in the topsoil layer (Jourdan & Rey 1997). The objective of this research was to determine the architecture of oil palm roots in response to soil humidity in the roots zone in its initial water footprint system.

MATERIALS AND METHODS

The research was conducted at the oil palm plantation of PT. Bio Nusantara, Central Bengkulu Province, Indonesia. The oil palms used in this research were mature palms (TM 14), of which 4, 7 and 14 refer to the age after first harvest. Research location was: TM 14 (3°37'3.26" SL and 102°16'16.35" EL)

The root was measured destructively (oil palm age of mature plants 4 year = TM 4) and non-destructively with parameters of study such as roots depth, roots length and roots density as oil palms have been producing for 14 years (TM 14 = the term on oil palm plantations in Indonesia). Data of root density from the classification of four roots was compared with the distance of stem-ends of the oil palm (Noordwijk & Purnomosidhi 1995). Soil physical properties was carried out in Soil Physical Laboratory in Soil Research Institution in Cimanggu, Bogor, Indonesia. Comparison of distribution condition or humidity pattern under the oil palm trees was measured in the field using microcontroller circuit apparatus with multichannel measurement of soil humidity sensor.

RESULTS AND DISCUSSION

Morphology of Oil Palm Root

Oil palm roots form a fibrous root system (*radix adventitia*), for example, if the embryo roots die or are subsequently followed by a number of roots that are approximately similar, and all come out from the stem-ends. The shape of oil palm roots is shown in Figure 1.

The capacity of water absorption by oil palm depends on the constituent components of root and stem in absorbing and transporting nutrients and water in a series of transpiration process and forming them into biomass during its growing process. The oil palm roots consisted of a vascular bundle which is a single chain of phloem and xylem tissues surrounded by parenchyma, the skin comprising endodermis, cortex and epidermis. The root-end consists of a root cell elongation zone, cell division tissue and root cap tissue with parenchyma predominating more than the vascular bundles (Figure 1).

The growth of oil palm roots is described as follows: the primary roots growing from the stem-ends in the soil to the sides (horizontal direction) and downwards (vertical direction), serves as an anchor for the plant. The secondary root branches out from the primary root, also towards the horizontal and vertical direction. The tertiary root branches out from the secondary roots primarily from the secondary roots that are horizontal near the soil surface, and the tertiary root bears the quaternary roots. This is in accordance with (Engels *et al*. 2005) who explained that horizontal roots that spread in the surface layer of the soil will grip the soil, and vertical roots serve to anchor the soil that structurally support the plant stand so it is not easily uprooted by the movement of the soil mass.

In the roots system, the roots that actively absorb water and nutrients (feeder root) are tertiary and quaternary roots. Depending on the plant material and soil type, the roots of oil palm can grow hor-izontally to more than 6 m and vertically about 1.5 to 5 m. The dead primary roots will soon be replaced with new ones. Observations on the radius around palm stands showed that more primary roots were found. The diameter of primary, secondary, tertiary and quaternary roots was 6-10 mm, 2-4 mm, 0.7-2 mm, and 0.1-0.3 mm respectively (Tinker 1976; Hartley 1977; Fatmawati & Ginting 1987; Siahaan *et al*. 1990; Lubis 1992).

The growth of oil palm roots in this study was observed in the horizontal and vertical directions. Horizontally, the roots were concentrated in the soil surface layer to a depth of 30 cm to meet their nu-trient needs. The soil surface layers generally contained higher nutrients and better aeration than the lower layers. Vertically, the roots grew downwards aiming for plant anchorage, so that the stems could grow up firmly and looked for nutrients and water (Figure 2a). At the beginning of development, roots grow in the surface layer and gradually deeper down the soil. Even though the bulk density of the soil is increasing, it turns out that the roots of oil palm can grow and develop to meet their needs.

Characteristics of Oil Palm Roots Architecture

The horizontal roots distribution pattern in this study was determined from the density of oil palm roots TM 14 by a non-destructive method using sample holes. Age of TM 14 was selected by considering that at this age, the plant's productivity was already stable. The measurement resulted from the density of oil palm roots TM 14 at Bio Nusantara, Bengkulu, showed that only a few primary roots (Ø>5 mm) were found at a depth of 0–

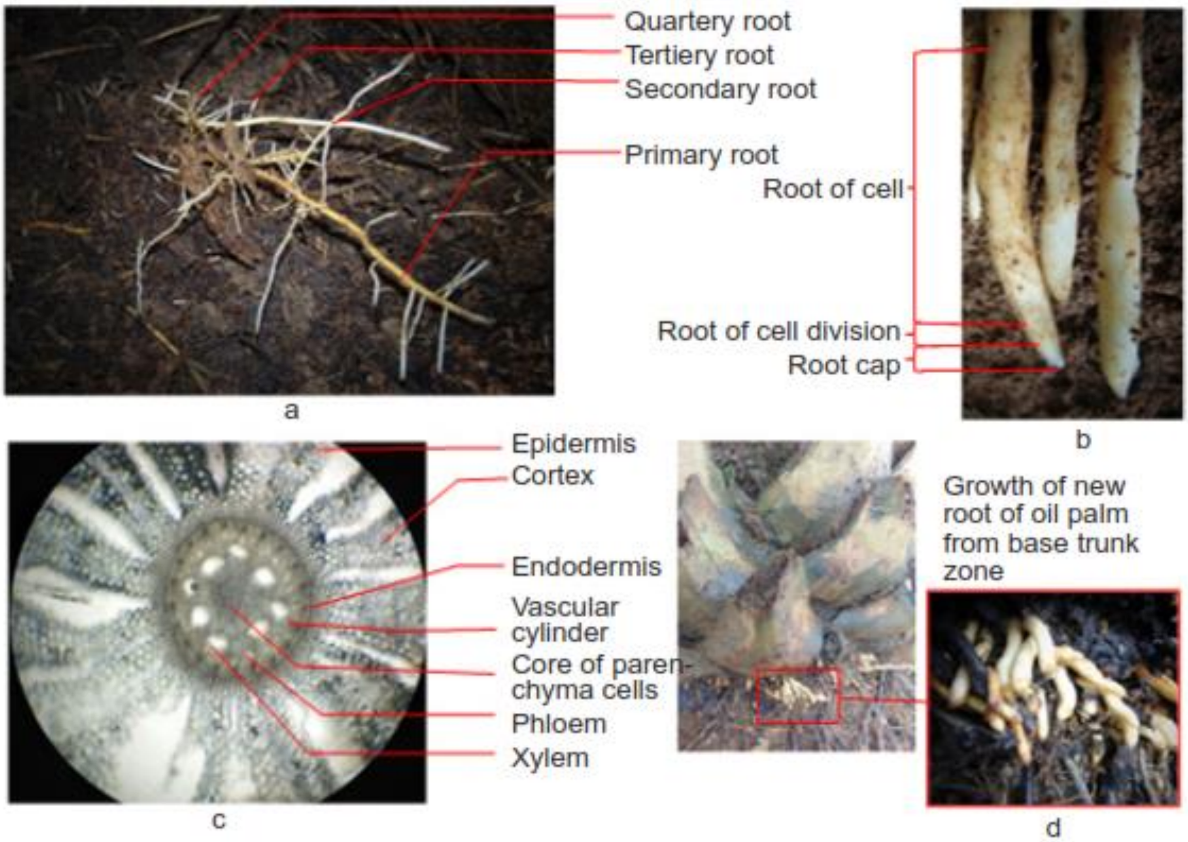

Figure 1 Morphology and anatomy of oil palm base: a Oil palm roots; b Primary root-ends; c Anatomical cross-section of the primary root; d Growth of new root from stem-ends of the oil palm.

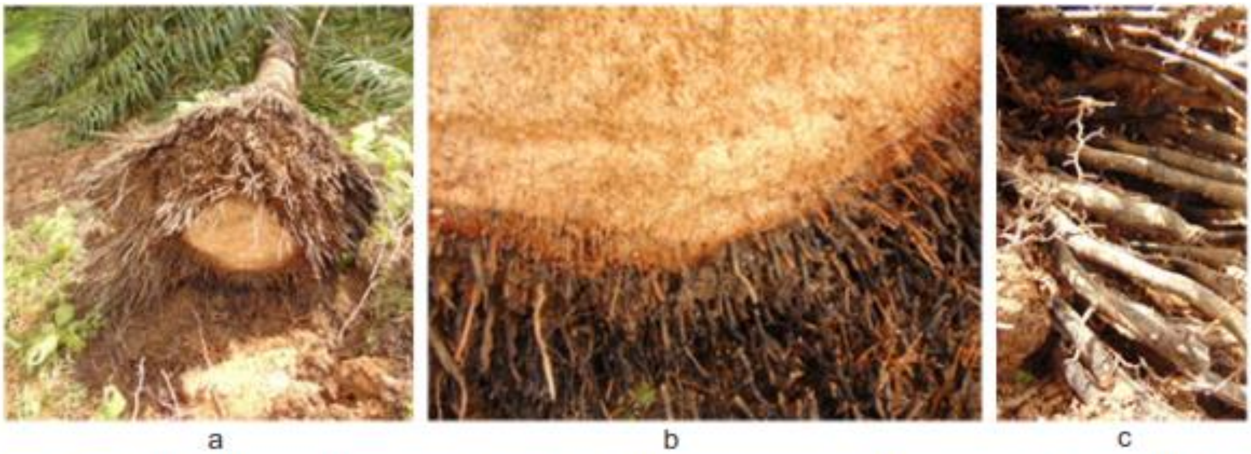

Figure 2 Crushing (destructive) of oil palm: a Horizontal roots (grip roots) separated from vertical roots (anchor roots); b Root tissue on oil palm stem tissue; c Tissue density on oil palm roots system.

20 cm. The average primary root density was up to radius 5.0 m from the stem-ends ranging about 0.018-0.077 g $dm^{3\ -1}$. The primary roots predominantly served to structurally support the oil palm tree so as to grow deeper. econdary roots density (Ø 2.5-5 mm) ranged between 0.312-0.665 g $dm^{3\ -1}$. The secondary roots generally spread evenly. This is good enough for oil palm because it may strengthen the stem stand. Similar to the primary roots, the role of secondary roots is to structurally support the oil palm stem.

Table 1 shows that at a depth of 0–20 cm, the soil is dominated by quaternary roots (Ø<0.5 mm), followed by tertiary roots (0.5≤Ø<2.5 mm). In general, density of quaternary and tertiary roots decrease along with the increase of the distance from the stem-ends. The average density of

Table 1 Average density of oil palm roots of mature palms (TM 14) at 0–20 cm of soil depth

Radius from stem-ends (m)	Average roots density (g m$^{3-1}$)			
	Primary	Secondary	Tertiary	Quaternary
1.0	0.077	0.574	0.962	1.877
2.0	0.035	0.665	0.981	1.385
3.0	0.018	0.312	0.492	0.577
4.0	0.018	0.422	0.165	0.308
5.0			0.088	0.192

quaternary roots up to a radius of 5.0 m from the stem-ends, which is between 0.187-1.877 g dm$^{3-1}$.

The density of tertiary roots is lower than the quaternary roots', ranging between 0.088-0.962 g dm$^{3-1}$. The distribution pattern of quaternary and tertiary roots shows that there is a correlation between the density of the roots and the radius from the stem-ends.

Table 2 shows that the pattern of roots' density at a depth of 20–40 cm is nearly similar to that at a depth of 0–20 cm, i.e. gradually decreasing along the increasing of the radius from the stem-ends. Additionally, the roots' density at a depth of 20–40 cm is lower than that at a depth of 0–20 cm of secondary, tertiary or quaternary.

Primary roots are found at a radius of 1.0 m and 2.0 m with the density value of 0.573 g dm$^{3-1}$ and 0.114 g dm$^{3-1}$. The secondary roots are only found up to a radius of 3.0 m from the stem-ends with a density value ranging between 0.051-0.422 g dm$^{3-1}$. The tertiary roots' density range between 0.027-0.912 g dm$^{3-1}$ while the quaternary roots range between 0.047-1.155 g dm$^{3-1}$. There is a strong correlation between the roots' density and the radius distance from the stem-ends.

As a comparison, destructive measurement was conducted by using TM 4 plants (Figure 3). The growth of primary roots at the surface zone (0.05-0.3 m) reaches up to a depth of 6 m, while at the 0.3–0.5 m zone they reach up to 3.5 m from the stem-ends. Secondary and tertiary roots develop at a depth of 0–2.0 m including at the zone of 2.5-4.5 m from the stem-ends. The growth of secondary and tertiary roots at that zone seems to branch out from the primary roots which grow at a depth between 0.05–0.5 m and soaked inside the ground with a higher density level. At the age of 14 years, the growth of primary roots at the first and second horizons has reached up to 6 m from the stem-ends. The growth of secondary and tertiary roots at the second, third, and fourth horizons at the 2.5–4.5 m zone show an increase in number.

The initial growth of the oil palm roots in horizontal direction starting at the surface layer is up to 4.5 m away from the stem-ends, while in vertical direction it is only up to 2.5 m away from the stem-ends. With the increase of age, at 2.5–4.5 m away from the stem-ends at a depth of 0.3–2.0 m, secondary and tertiary roots branch out from primary roots soaked from the surface to a deeper layer reaching 2.0 m deep.

The growth of primary roots in horizontal direction shows better result than that in vertical direction (Figure 4). This shows that the downward growth has been restricted due to mechanical obstacles such as higher soil compaction at the deeper side compared with the surface layer. In horizontal direction, the growth of primary roots of mature oil palm, age 14 years (TM14), can only reach up to 0–0.5 m of depth and in vertical direction it can only reach up to 2.5 m from the stem-ends. In soil condition with high compaction in the subsoil layer, it seems that secondary roots can replace the function of primary roots as anchor, and absorb water from the lower layer. Smaller diameter of the secondary roots than the primary roots makes it easier to grow on a high

Table 2 Average density of oil palm roots of mature palms (TM 14) at 20–40 cm of soil depth

Radius from stem-ends (m)	Average roots density (g m$^{3-1}$)			
	Primary	Secondary	Tertiary	Quaternary
1.0	0.573	0.422	0.912	1.155
2.0	0.114	0.208	0.593	0.780
3.0		0.141	0.348	0.468
4.0		0.051	0.215	0.275
5.0			0.027	0.047

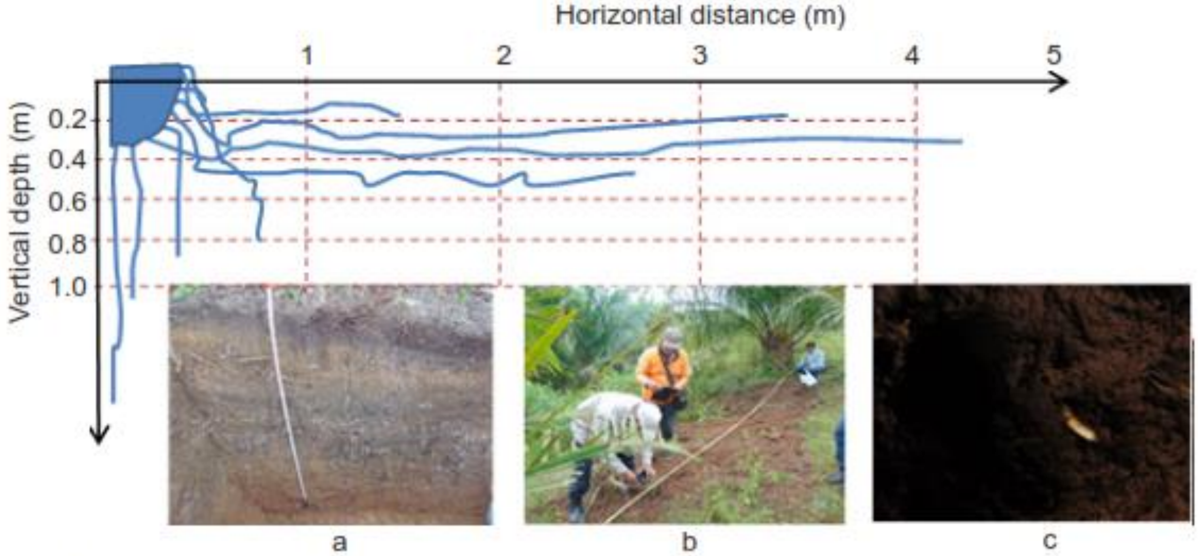

Figure 3 Architecture description of oil palm primary roots resulted from destructive measurement: a Excavation of soil around the palm roots; b Activity of measuring the root length of the palm at ground level; c The primary root tip that grows actively in the soil.

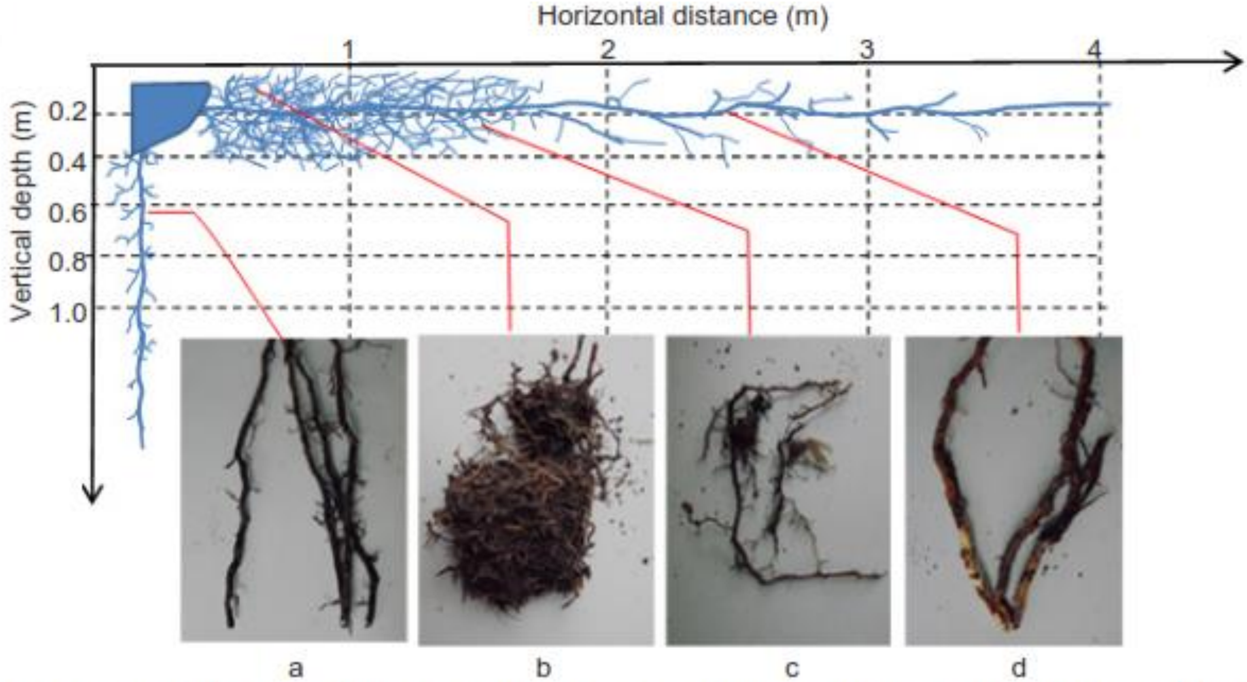

Figure 4 Architecture description of oil palm root parts system resulted from destructive measurement: a Anchor roots; b Mat of quartery and tertiary roots; c Secondary roots; d Primary roots.

compaction soil especially when the primary roots can not grow in that soil.

The growth of tertiary roots (lateral roots) appears to be away from the stem-ends and is not affected by the soil compaction level. Roots proportionally grew to whole directions. This shows that tertiary roots become the pioneer roots to soak the soil. In addition, tertiary roots also become the roots which absorb the nutrients. Thus, as long as tertiary roots grow well, the oil palm can grow and develop normally. This suggests that the mechanism of roots development in the soil layer with high compaction is always initially started by the penetration of tertiary roots, followed by secondary roots, and finally by primary roots, able to soak and develop in compacted soil. Penetration of tertiary and secondary roots into high bulk density soil makes physical and chemical processes to occur, making primary roots easier to penetrate the soil (Bucio *et al*. 2003; Malamy 2005; Osmont *et al*. 2007; Nibau *et al*. 2008; Malamy 2010). According to Russel (1982), if the growth of primary roots are inhibited, they will bear secondary roots. If the secondary roots are inhibited, they will bear tertiary roots in which the diameter corresponds with the size of soil pores (Lynch 1995; Lynch 2011).

During their growth, roots contribute various organic matters into the soil including mucigel, dead cell roots, hair roots secretion and exudate. These organic materials are then directly destroyed by soil-decomposing microorganisms producing humus and organic acids (Russel 1982; Fogel 1985). If these organic materials are over-decomposed, organic acids such as humic acid are released, which are capable of changing soil's physical and chemical properties. Jourdan & Rey (1997) stated that total biomass of oil palm, age 3 years, in the form of roots is 3 tons ha^{-1} and 16 years is 55 tons ha^{-1}. About 29–40% of the total is dead and decomposed in the soil forming humic material. According to Russel (1982), these organic material compositions are carbohydrate, protein (amino acids), organic, enzyme and other materials that can be used as inhibitor or trigger for the growth of fungi, bacteria and other micro-organisms. These organic compounds are usually used by soil-decomposing microbes as energy sources. This condition makes population of rhizosphere microbes higher compared with soil located far from the plant roots (Rao 1994). Microbial activity and final bacillus decomposition of organic material in the form of acid, organic acid, is believed to be active in changing the properties of both soil, chemically and physically. This change is expected to create an environment suitable for roots to grow and develop optimally. Chan, Watson and Lim (1980) stated that besides roots, which can be used as an organic matter source for oil palm, leaf bark also contributes to about 10 tons a year^{-1} of dry matter, while empty fruit bunches contributes to 1.5 tons a year^{-1} of dry matter, and oil palm tree, age about 25–30 years, contributes to about 74.5 tons ha^{-1} of dry matter.

Oil Palm Root Architecture in Respone to Soil Humidity

The finer the roots, the easier they die out and be replaced by new ones. This process contributes to the pore formation. Mineral decomposition due to organic activities which changes soil aggregation also contributes to ease the roots growth.

The ability of root growth in a high compacted soil seems to be affected by plant age, as can be seen that the growing of the roots is wider along with the increase of age. In addition, it also depends on the fertility of the oil palm in which fertile oil palm trees have good root growth and development.

The observation of oil palm plant architecture which resulted from the destructive method by destructing the oil palm roots using water spray carefully is shown in Figure 5. That image shows a simple architecture of a root system:

horizontally gripping the soil and vertically anchoring the stem into soil. Active horizontal root tissues are always renewed by new roots coming out from the stem-ends. The horizontal root mats located at a 0–1.5 m radius and 0-0.4 m of depth are very solid, consisting of primary, secondary, tertiary and quaternary roots as well as roots inside the nets mat. That condition also promoted the replacement of dead roots with the new roots. The root mat is very unique, forming a net of roots which is able to capture and control water availability in soil surface environment around the growing space under the oil palm tree. This is also confirmed by laboratory analysis of soil physical properties of this field study as seen on Table 3.

In general, based on Table 3, the water content of the lower soil layer at a depth of 40-60 cm is higher than that of the upper layer depth of 20-40 cm, and also the most upper layer of 0-20 cm. The surface is the highest layer experiencing water content fluctuation due to rainfall, root uptake and evaporation (Hanks & Ascroft 1986), thus having lower water content.

Soil porosity of all oil palm locations tend to be found at a depth over 0.4 m. This is presumably due to soil compaction from oil palm root tissue penetration and high rainfall rate which penetrated the soil surface. According to Rachman *et al*. (2013) the pore size and inter-porous correlation determine the permeability, high or low. Water can easily flow inside the soil which has big pores and good inter-porous correlation. Small pores with uniform inter-porous correlation have smaller permeability thus water will flow inside the soil more slowly.

The result of soil pore analysis shows insignificantly different values, but shows slightly higher porosity at 20-40 cm of depth. This shows that oil palm roots are able to form a water capture zone under the horizontal root system to maintain water loss on the surface or at an active horizontal roots zone.

As a comparison, a measurement was made by using soil humidity multichannel microcontroller sensor placed in a hole under an oil palm tree. The measurement result of soil humidity distribution pattern under the oil palm tree (roots zone) is shown in Figure 6. The contour pattern obviously shows a variation of water content distribution in several depth zones due to dynamic water movement in the oil palm roots zone.

This shows that the anatomy and morphology in architecture of oil palm roots have naturally adapted to form a system of roots which are able to maintain the mechanism of water availability balance for the growth and development of oil fruit plants. The water footprint system is only active at the surface zone (0-0.8 m) while at a depth over 0.8 m it is merely affected by local aquifer condition.

CONCLUSION

Oil palm roots grow to horizontal and vertical directions. In horizontal direction, roots are concentrated at the soil surface layer up to 0.3 m of depth for nutrients content uptake. In vertical direction, roots grow downward, acting as an anchor so that the stem grows upwards firmly and catches nutrients and water. The dead primary roots will soon be replaced with new roots. Primary roots predominantly served to structurally support the plant, thus these roots may grow into deeper layers of the soil.

The growth of primary roots in horizontal direction shows better result than in vertical direction. Smaller diameter of secondary roots than primary roots makes them easier to grow on a high compaction soil, especially when the primary roots can not grow at that soil. The growth of tertiary roots appears to be staying away from the stem-ends and are not affected by the soil compaction level. Finer diameter of the roots dies more easily

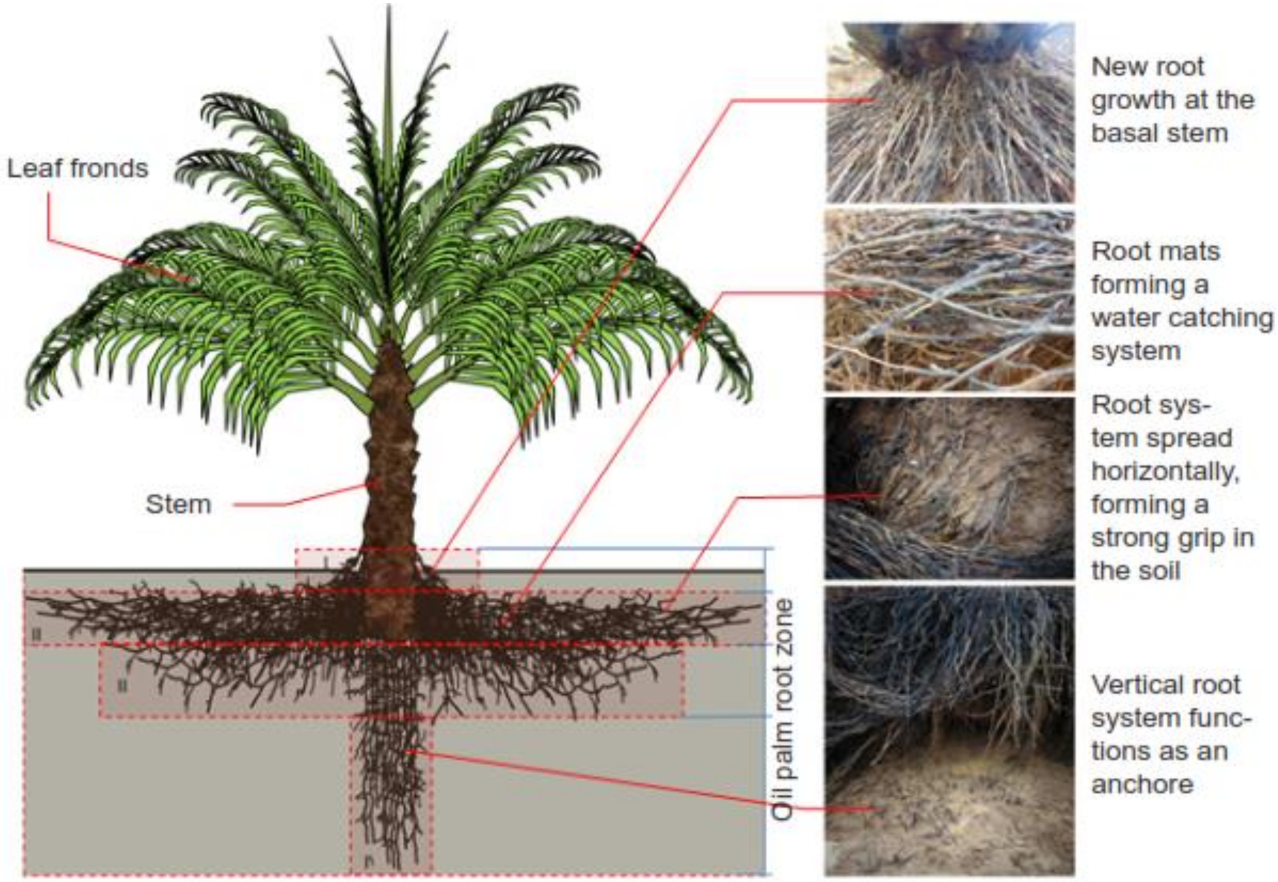

Figure 5 Oil palm roots architecture at the roots zone and its parts which is shown by the image resulted from the destructive measurement method.

Table 3 Laboratory analysis result on soil physical properties of research location

Plant location	Depth layer	Water content	Bulk density	Particle density	Pore space	Water content				Dominant pore		Water avail-ability
						pF1	pF2	pF 2.54	pF 4.2	Quick	Slow	
	(cm)	(%)	g cc^{-1}	g cc^{-1}	%	%	%	%	%	%	%	%
TM 14	0-20	33.16	1.10	2.84	61.4	56.1	48.9	43.5	29.6	12.5	5.4	13.9
3°37'3.26"SL	20-40	31.73	1.28	2.35	45.6	43.7	35.2	31.4	20.8	10.4	3.8	10.6
102°16'16.35"EL	40-60	32.45	1.18	2.31	49.0	44.2	38.0	33.6	20.9	11.0	4.4	12.7

and are replaced with new root. This process contributes in forming pores. Mineral decomposition due to organic activities which changes soil aggregation form also contributes to ease the growth of roots.

An active horizontal roots net mats is always renewed with new roots arising from the stem-ends of the oil palm plant. The horizontal roots mats is located at a radius of 0–1.5 m at a depth of 0–0.4 m which is very solid for primary, secondary, tertiary and quaternary roots as well as the soil located in the net mats. This condition actively changes the dead roots with new ones. The roots net mats is very unique, forming a net mats that can capture and control water availability in the soil surface environment around the growing space of oil palm plant. The anatomy and morphology in architecture of the oil palm roots have

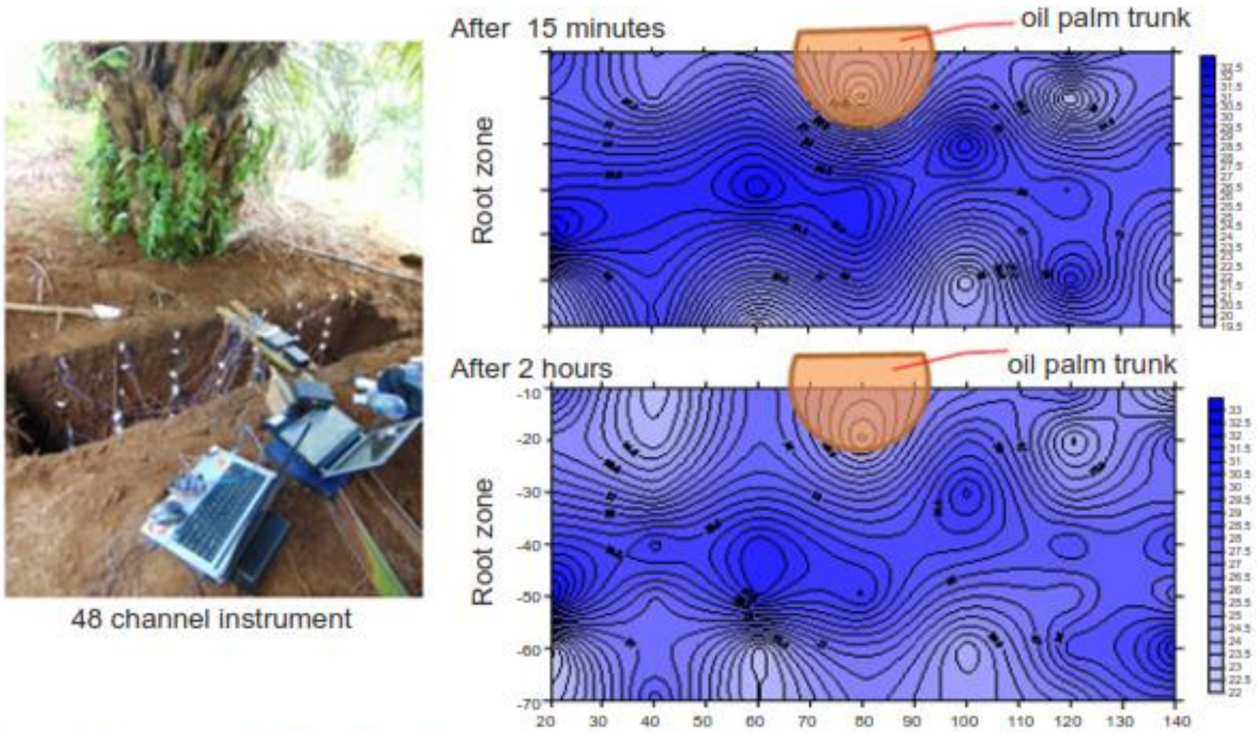

Figure 6 Water content distribution pattern resulted from 48 channel instrument under the oil palm trees of PT Bio Nusantara.

naturally adapted to form a roots system that can conduct a mechanism to maintain soil availability of water balance for oily fruits growth and production. The water footprint system is only active at the surface zone (0–0.8 m), while deeper than 0.8 m it is more affected by local aquifer condition.

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